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Preliminary Numerical Study of the Outer Scale Size of Ionospheric Plasma Cloud Striations

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The one level, two-dimensional fluid equations modelling striation development in large F region ionospheric plasma clouds have been numerically solved, using an initial one-dimensional cloud geometry, for three different initial Pedersen conductivity gradient scale lengths L = 3, 6, 10 km. In the nonlinear regime evidence is presented for an outer scale size of well developed striations in a direction (y) perpendicular to the ExB drift (x) of the plasma cloud whose initial Pedersen conductivity varies only along the drift direction. The perpendicular outer scale size $2\pi/k_{oy}$ is

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20. Abstract (Continued)

proportional to the initial gradient scale length L through a constant of order unity, i.e., $k_{oy}L/2\pi \simeq 1$. In addition, for the three scale lengths L studied, the one-dimensional x power spectra $\propto k_x^{-n_x}$ with $n_x \simeq 2$ for $2\pi/k_x$ between 1 and 80 km while the y power spectra $\propto k_y^{-n_y}$ with $n_y \simeq 2$-2.5 for $2\pi/k_y$ between 1 and 10 km. These results are consistent with recent experimental [Baker and Ulwick, 1978; Kelley et al, 1979] and theoretical studies [Scannapieco et al, 1976; Chaturvedi and Ossakow, 1979] of plasma cloud striations.

CONTENTS

INTRODUCTION

It is well known that artificial plasma clouds injected into the ionosphere develop large scale visible striations on a time scale of minutes to hours depending on ambient conditions. At late times, these striations (fingers) are nearly uniform parallel to the earth's magnetic field but are highly structured perpendicular to the field. Many features of striation development can be explained by applying [Linson and Workman, 1970; Perkins, et al., 1973] the $\underline{E}\times\underline{B}$ gradient drift instability [Simon, 1963] to plasma cloud geometries. As demonstrated by recent experiments conducted by the Defense Nuclear Agency (DNA) in the STRESS (Satellite Transmission Effects Simulations) program significant scintillation in signal phase and amplitude can occur for line-of-sight propagation through this structured region [Prettie et al., 1977]. A direct input into propagation studies through plasma cloud striated environments is the spatial power spectrum of the striations or distribution of striation scale sizes. Experimental [Baker and Ulwick, 1978; Kelley et al., 1979] and theoretical studies [Scannapieco et al., 1976; Chaturvedi and Ossakow, 1979] have indicated that the power spectra of striated plasma clouds follow a power law $\propto k^{-n}$, $n \simeq 2$-3 for scale sizes $2\pi/k$ in the range of 0.05 to 100km. Several years ago Rufenach [1974] showed that naturally occurring density irregularities in the F region ionosphere should be described by a power law with a large outer scale dimension ($\sim$ 100 km). However, to date, there has been no quantitative experimental or theoretical study of the outer scale size of plasma cloud striations.

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The purpose of the present work is to determine the outer scale size of striated ionospheric plasma clouds through direct numerical solution of the fundamental fluid equations which model the $\underline{E}\times\underline{B}$ gradient drift instability. The results to be presented extend previous numerical simulations [Scannapieco et al., 1976] and are consistent with recent experimental data [Baker and Ulwick, 1978; Kelley et al., 1979].

MODEL EQUATIONS

We wish to compute the outer scale size of large ionospheric plasma clouds at altitudes such that the electron and ion collision frequencies are small compared to their gyrofrequencies (F region). In particular, the following analysis could apply to large barium clouds released at altitudes greater than approximately 200 km. The restriction to large clouds (large integrated Pedersen conductivity compared with that of the background ionosphere) allows the neglect of the cloud interaction with the background ionosphere (second level) and simplifies considerably the analytical and numerical analysis of cloud evolution. For wavelengths much greater than the ion gyroradius ($\sim$ 10 meters for Ba^+ in twlight F region) fluid equations can be used which for large clouds have been given many times [Völk and Haerendel, 1971; Perkins et al., 1973; Zabusky et al., 1973; Ossakow et al., 1975; McDonald et al., 1978].

By adopting a Cartesian coordinate system (x, y, z) with magnetic field $B\hat{\underline{z}}$, ambient electric field $E_o\hat{\underline{y}}$, assuming all variables are independent of z, and ignoring to lowest order electron and ion inertia, we can write, after transforming to a frame moving with the ambient plasma

drift $\underline{V}_o = (cE_o/B)\hat{\underline{x}}$

$$\frac{\partial \Sigma}{\partial t} + \frac{c}{B} \hat{\underline{z}} x \nabla\varphi \cdot \nabla\Sigma = 0 \tag{1}$$

$$\nabla \cdot \Sigma \nabla \varphi = \underline{E}_o \cdot \nabla\Sigma \tag{2}$$

where Σ is the magnetic field line integrated Pedersen conductivity at the cloud level, B is the magnetic field, $\hat{\underline{z}} = \underline{B}/|B|$, $\nabla\varphi = -\underline{E}(x,y) - E_o\hat{y}$ where E_o is the ambient applied perpendicular electric field. All other symbols retain their conventional meaning.

Linearizing equations (1) and (2) and assuming fluctuations $\delta\Sigma, \delta\varphi$ of the form $\exp[i(k_y y + k_x x) + \gamma_{\underline{k}} t]$ it can easily be shown that the usual gradient drift ($\underline{E}x\underline{B}$) instability growth rate is $\gamma_{\underline{k}} = (cE_o/BL)(k_y/k)^2$ where $k^2 = k_x{}^2 + k_y{}^2$ and $L^{-1} = \partial \ell n \Sigma_0/\partial x$. Note that this model predicts no preferred scale size and all modes with fixed k_y/k have the same growth rate.

As has been previously shown [McDonald et al., 1978] eq. (1) and (2) can be put into dimensionless form by normalizing $\underline{x} \equiv (x,y), t, \Sigma, \underline{V}$, φ by L_o, L_o/V_o, Σ_o, V_o, L_oE_o, respectively, giving

$$\frac{\partial \Sigma}{\partial t} + \hat{\underline{z}} x \nabla\varphi \cdot \nabla\Sigma = 0 \tag{3}$$

$$\nabla \cdot \Sigma \nabla \varphi = \partial\Sigma/\partial y \tag{4}$$

where L_o is an arbitrary length scale and all quantities in (3) and (4) are understood to be dimensionless.

NUMERICAL SIMULATIONS

Equations (3) and (4) were solved numerically over a mesh of 258 grid points in the x-direction (the $\underline{E}_o \times \underline{B}$ direction) and 102 points in the y-direction. Using a constant grid spacing of 310 m, the real space dimensions of the mesh were 80 km along x and 31 km along y. The cloud integrated Pedersen conductivity Σ in equation (3) was advanced in time using a multidimensional flux-corrected variable time step leapfrog-trapezoid scheme [Zalesak, 1979] which is second order in time and fourth order in space. At each timestep, the self-consistent cloud potential φ was found from equation (4) using a Chebychev iterative method [Varga, 1962; McDonald, 1977] which normally converged to within 5×10^{-4}. Periodic boundary conditions were imposed in the y-direction with Neumann conditions along the x-direction ($\partial/\partial x = 0$). These boundary conditions result in a realistic representation of plasma inflow-outflow in the wind direction (x).

The principal diagnostics of these simulations were the time history of real space conductivity $\Sigma/\Sigma_o \equiv \tilde{\Sigma}$, potential φ, and associated spatial power spectra. These power spectra were obtained by first Fourier transforming the real space cloud conductivity $\delta\tilde{\Sigma}(x,y) \rightarrow \delta\tilde{\Sigma}(k_x,k_y)$. The power spectral density $|\delta\tilde{\Sigma}(k_x,k_y)|^2$ was then formed and one-dimensional power spectra $P(k_x)$ and $P(k_y)$ were computed where

$$P(k_x) = \int dk_y \; | \delta\tilde{\Sigma} \; (k_x,k_y)|^2$$

and (5)

$$P(k_y) = \int dk_x \; | \delta\tilde{\Sigma} \; (k_x,k_y)|^2$$

The power spectra $P(k_x)$ and $P(k_y)$ were then fitted with a three parameter (spectral stength $P_{o\alpha}$, spectral index n_α, and outer scale wavenumber $k_{o\alpha}$) power law of the form

$$P(k_\alpha) = P_{o\alpha}(1+(k_\alpha/k_{o\alpha})^2)^{-n_\alpha/2} \qquad (6)$$

where α = x or y. Two different methods were used to extract the best fit parameters $P_{o\alpha}$, n_α, $k_{o\alpha}$. The first is a nonlinear least squares procedure which yields $P_{o\alpha}$ and n_α directly and then iterates to locate $k_{o\alpha}$. The second is a grid search technique through the three-dimensional space defined by $P_{o\alpha}$, n_α, $k_{o\alpha}$. Each parameter is varied independently to find the best least-squares fit. Faster convergence was found using the first technique.

Initially, the plasma cloud conductivity was taken to be of the form

$$\Sigma(0,x,y) = [\exp(-x/L)^2 + 0.1](1 + \epsilon(x,y)) \qquad (7)$$

where ϵ (x,v) has an rms value of 3%, and is generated from a ramdomly phased Gaussian power spectrum. Three computer runs were made distinguished by different initial conductivity scale lengths L = 3, 6, 10 km. In all cases, V_o = 100 m/sec and the maximum integrated cloud Pederson conductivity was approximately 10 times larger than the integrated background

ionospheric Pedersen conductivity at the cloud level.

Fig. 1a-d give representative time samples of the evolution of the real space isodensity conductivity contours for the intermediate case ($L = 6$ km). Fig. 1a shows the initial conductivity profile while Fig. 1b displays the cloud structure at $t = 260$ sec where backside steepening has occurred with jetting to the frontside. At $t = 560$ sec, elongation and striation are evident with bifurcation of the larger fingers already begun. Further elongation and bifurcation are seen in Fig. 1d ($t = 900$ sec). Similar shapes and morphologies are seen in the other two cases ($L = 3$, 10 km) but on different time scales.

Fig. 2 gives representative one-dimensional power spectra both parallel (x) and perpendicular (y) to the plasma cloud drift for the case $L = 6$ km and illustrates the outer scale turnover seen in the perpendicular (y) direction in all three runs ($L = 3$, 6, 10 km). These results are consistent with in situ experimental measurements [Baker and Ulwick, 1978; Kelley et al., 1979] made during recent DNA STRESS experiments. It should also be noted that in the two level numerical simulation of Scannapieco et al., [1976], where $L = 8$ km, a turnover in the power spectrum, in the direction perpendicular to $\underline{E}_o \times \underline{B}$, was also observed.

The time histories of the best-fit spectral indices n_x and n_y both in the parallel (x) and perpendicular (y) directions for $L = 10$ km are displayed in Fig. 3. After initial transients, the spectral index n_x

in the wind direction is approximately 2 while in the transverse direction $n_y \simeq 2$-2.5. These spectral indices are also noted in the other two cases (L = 3, 6 km) and are in agreement both with experiment $n \simeq$ 2.5 [Baker and Ulwick, 1978] and previous numerical simulations at L = 8 km where n_x, $n_y \simeq 2$-2.5 [Scannapieco et al., 1976].

In order to quantify further the outer scale size in the direction perpendicular (y) to the drifting cloud we have plotted in Fig. 4 the time evolution of $k_{oy} L/2\pi$ for the three cases studied (L = 3, 6, 10 km). After an initial transient period in each case the perpendicular outer scale size $2\pi/k_{oy}$ becomes steady and approximates the initial parallel conductivity gradient scale length L. This "freezing" of the outer scale size or suspension of further bifurcation was also noted in recent NASA sponsored barium releases in Alaska [J. Fedder, private communication, 1979]. In addition, the magnitudes of the outer scale sizes computed in these simulations are in agreement with the outer scales derived from preliminary analyses of DNA conducted barium cloud experiments over Florida [M. C. Kelley, private communication, 1979]. It should be noted that the linear theory of the $\underline{E} \times \underline{B}$ gradient-drift instability in plasma clouds cannot explain the scaling of the perpendicular outer scale size $2\pi/k_{oy}$ with the parallel initial gradient scale length L for two reasons. First, this scaling was gleaned from the well-developed striated nonlinear regime where linear theory is not applicable. Second, linear theory does not predict an outer scale turnover in the perpendicular direction since there is no linear damping (diffusion) in this model.

SUMMARY

We have numerically solved the one level, two-dimensional fluid equations which model striation development in large F region ionospheric barium clouds. In the nonlinear well-striated regime, evidence is presented for an outer scale size in the perpendicular (y) direction to the $\underline{E}\times\underline{B}$ drift (x) of large clouds in which the initial Pedersen conductivity varies only along its drift (x). For three initial cloud Pedersen conductivity gradient scale lengths L = 3, 6, 10 km the perpendicular outer scale size $2\pi/k_{oy}$ becomes steady with magnitude such that $k_{oy}L/2\pi \sim 1$. In addition, these simulations show that the one-dimensional parallel (x) power spectra $\propto k_x^{-n_x}$ with $n_x \simeq 2$ for $2\pi/k_x$ between 1 and 80 km while the perpendicular (y) power spectra $\propto k_y^{-n_y}$ with $n_y \simeq 2\text{-}2.5$ for $2\pi/k_y$ between $\sim$1 and $\sim$10km. These results are consistent with recent experimental [Baker and Ulwick, 1978; Kelley et al., 1979] and theoretical studies [Scannapieco et al., 1976; Chaturvedi and Ossakow, 1979] of plasma cloud striations.

Future studies are planned which include variation of initial and boundary conditions, addition of inertial effects and coupling to other ionospheric levels so that a parametric determination of the outer scale size of ionospheric plasma clouds can be achieved. Also, the numerical simulations will be run to later times.

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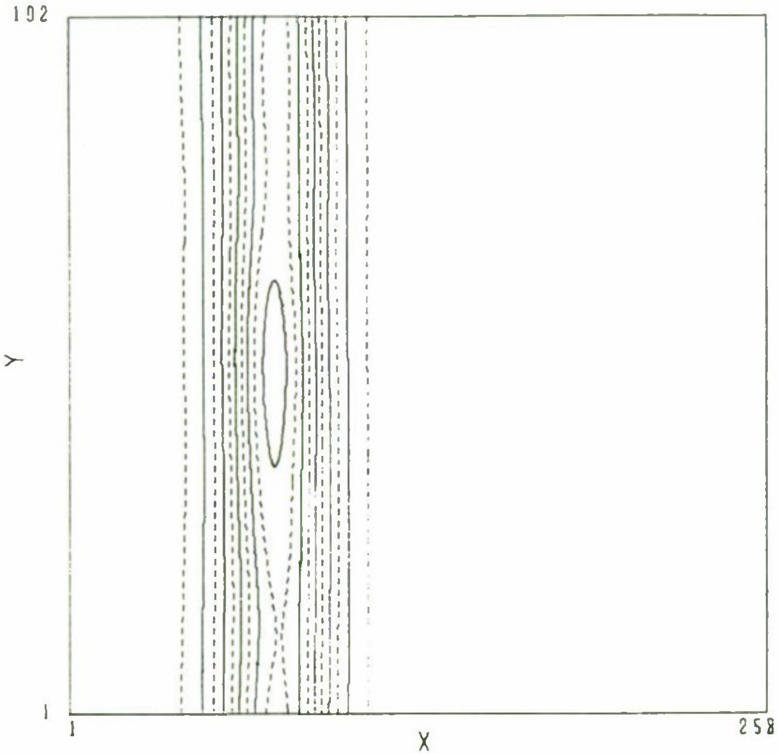

Fig. 1a

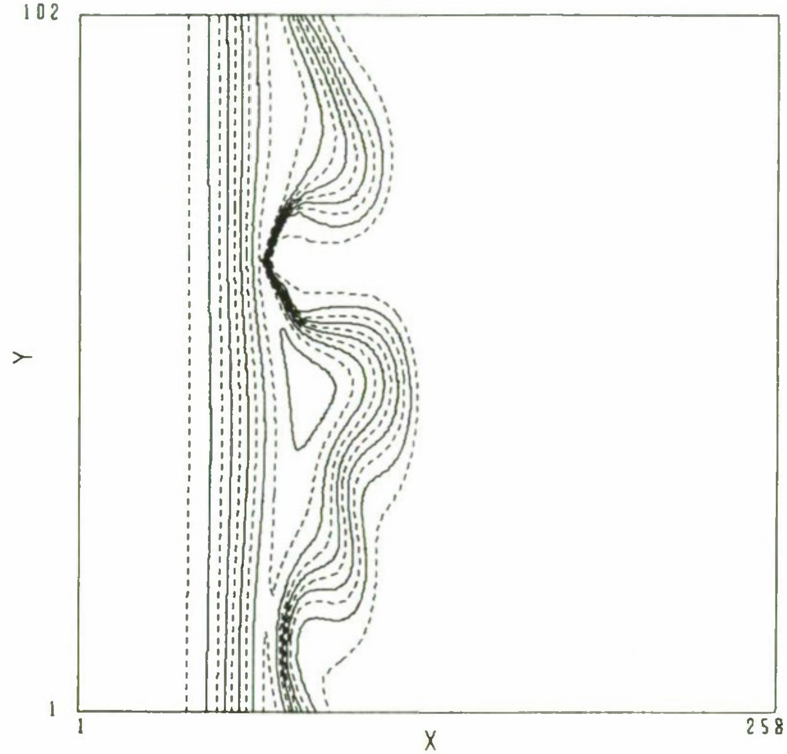

Fig. 1b

Fig. 1 - Real space isodensity contour plots of $\Sigma(x,y)/\Sigma_o$ for L = 6 km at (a) t = 0 sec, (b) t = 260 sec, (c) t = 560 sec, (d) t = 900 sec. Ten contours are plotted in equal increments from 0.1 to 1 with every other contour represented by a dashed line. The **x**-axis (y-axis) denotes the $\underline{E}_o \times \underline{B}$ ($\underline{E}_o$) direction with $\underline{B}$ out of the page. The numbers 258 and 102 refer to numbers of grid points in x and y directions. The x-axis has been compressed relative to the y-axis by a factor of 2.5. The "pinching off" of material in (c) and (d) is due to plotting format.

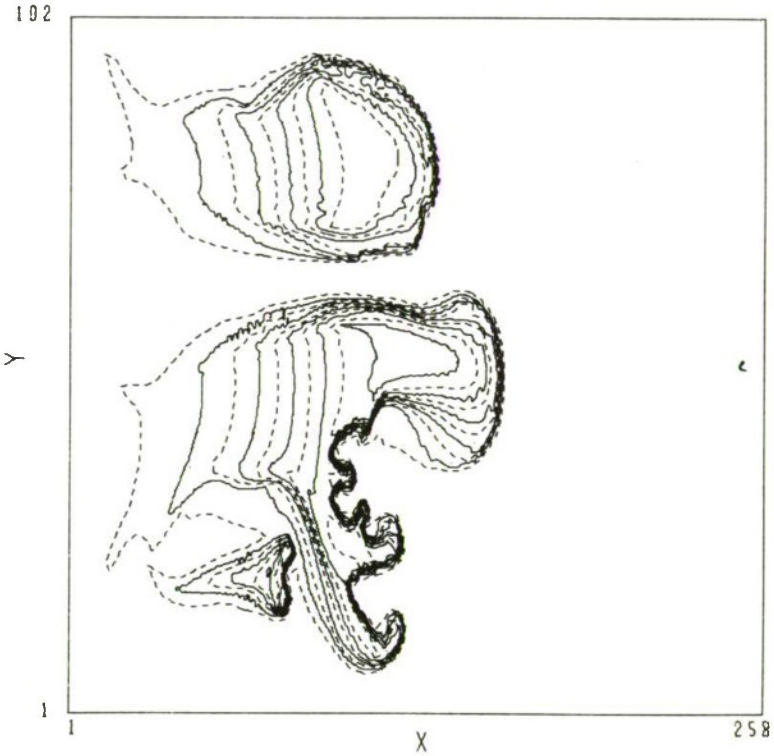

Fig. 1c

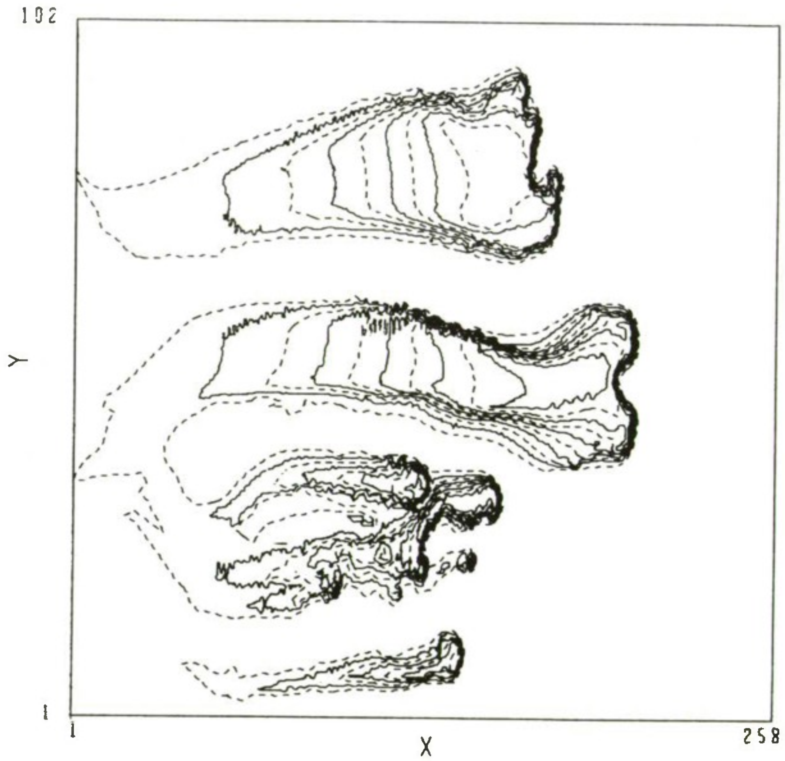

Fig. 1d

Fig. 1 - Real space isodensity contour plots of $\Sigma(x,y)/\Sigma_o$ for L = 6 km at (a) t = 0 sec, (b) t = 260 sec, (c) t = 560 sec, (d) t = 900 sec. Ten contours are plotted in equal increments from 0.1 to 1 with every other contour represented by a dashed line. The x-axis (y-axis) denotes the $\underline{E}_o \times \underline{B}$ ($\underline{E}_o$) direction with $\underline{B}$ out of the page. The numbers 258 and 102 refer to numbers of grid points in x and y directions. The x-axis has been compressed relative to the y-axis by a factor of 2.5. The "pinching off" of material in (c) and (d) is due to plotting format.

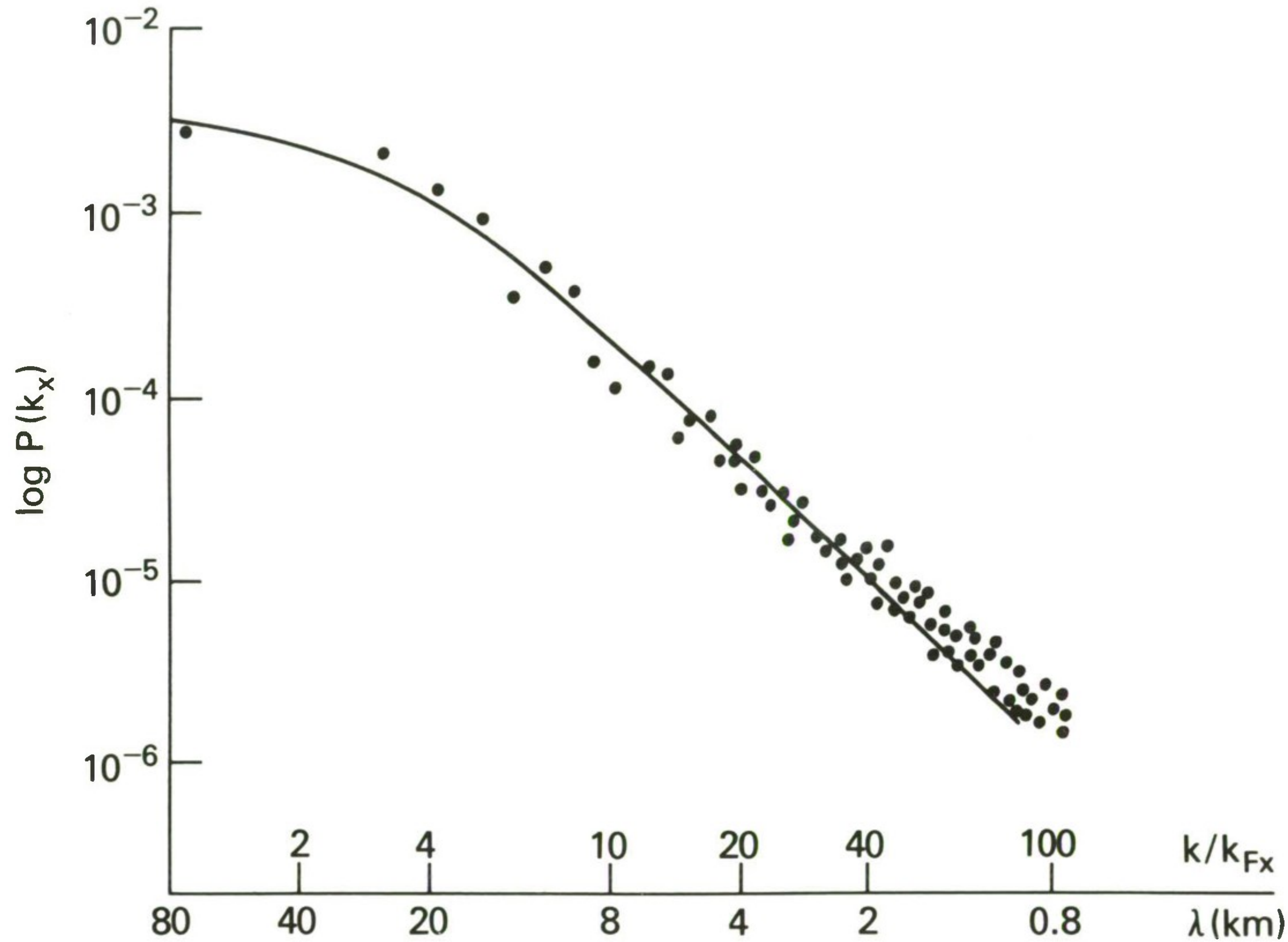

Fig. 2a - One dimensional (a) x power spectra and (b) y power spectra at t = 900 sec for L = 6 km. In (a), $k_{Fx} = 2\pi/80\ km^{-1}$ while in (b), $k_{Fy} = 2\pi/30\ km^{-1}$. The dots represent the numerical simulation results; solid curve is least squares fit which gives (a) $n_x = 2.1$, (b) $n_y = 2.5$. Note outer scale turnover in (b).

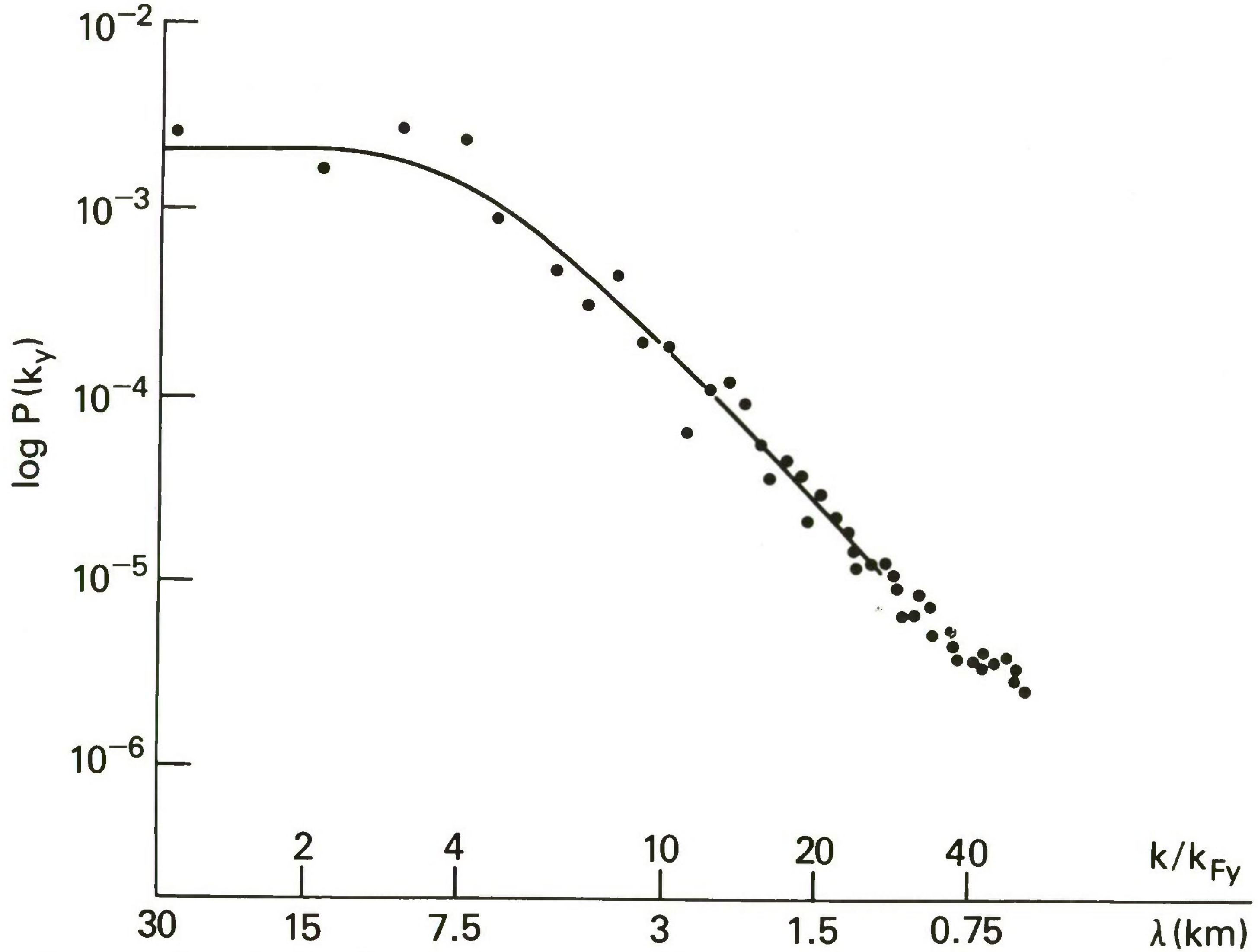

Fig. 2b - One dimensional (a) x power spectra and (b) y power spectra at t = 900 sec for L = 6 km. In (a), $k_{Fx} = 2\pi/80$ km^{-1} while in (b), $k_{Fy} = 2\pi/30$ km^{-1}. The dots represent the numerical simulation results; solid curve is least squares fit which gives (a) $n_x = 2.1$, (b) $n_y = 2.5$. Note outer scale turnover in (b).

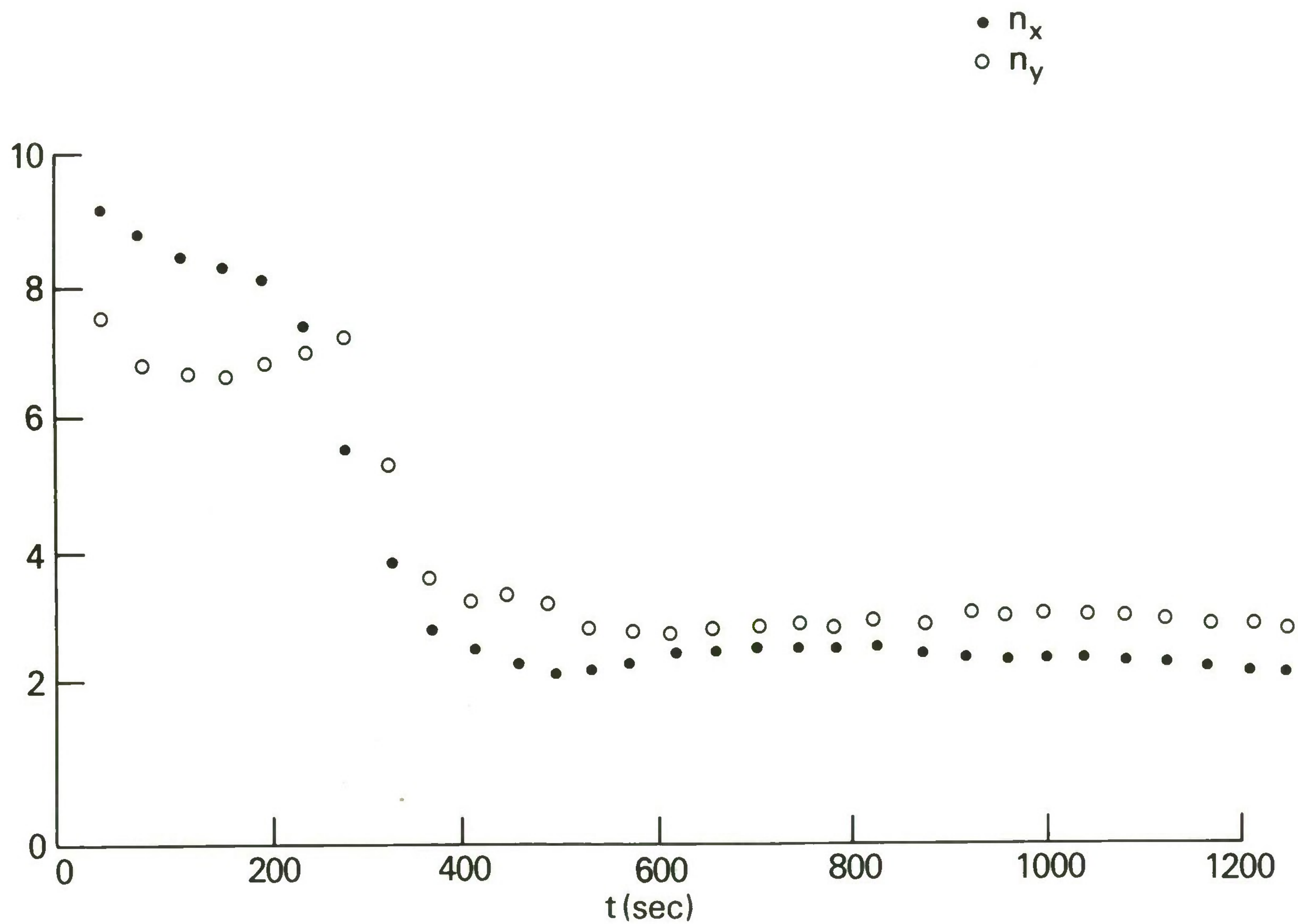

Fig. 3 - Time history of best fit spectral indices n_x and n_y for L = 10 km

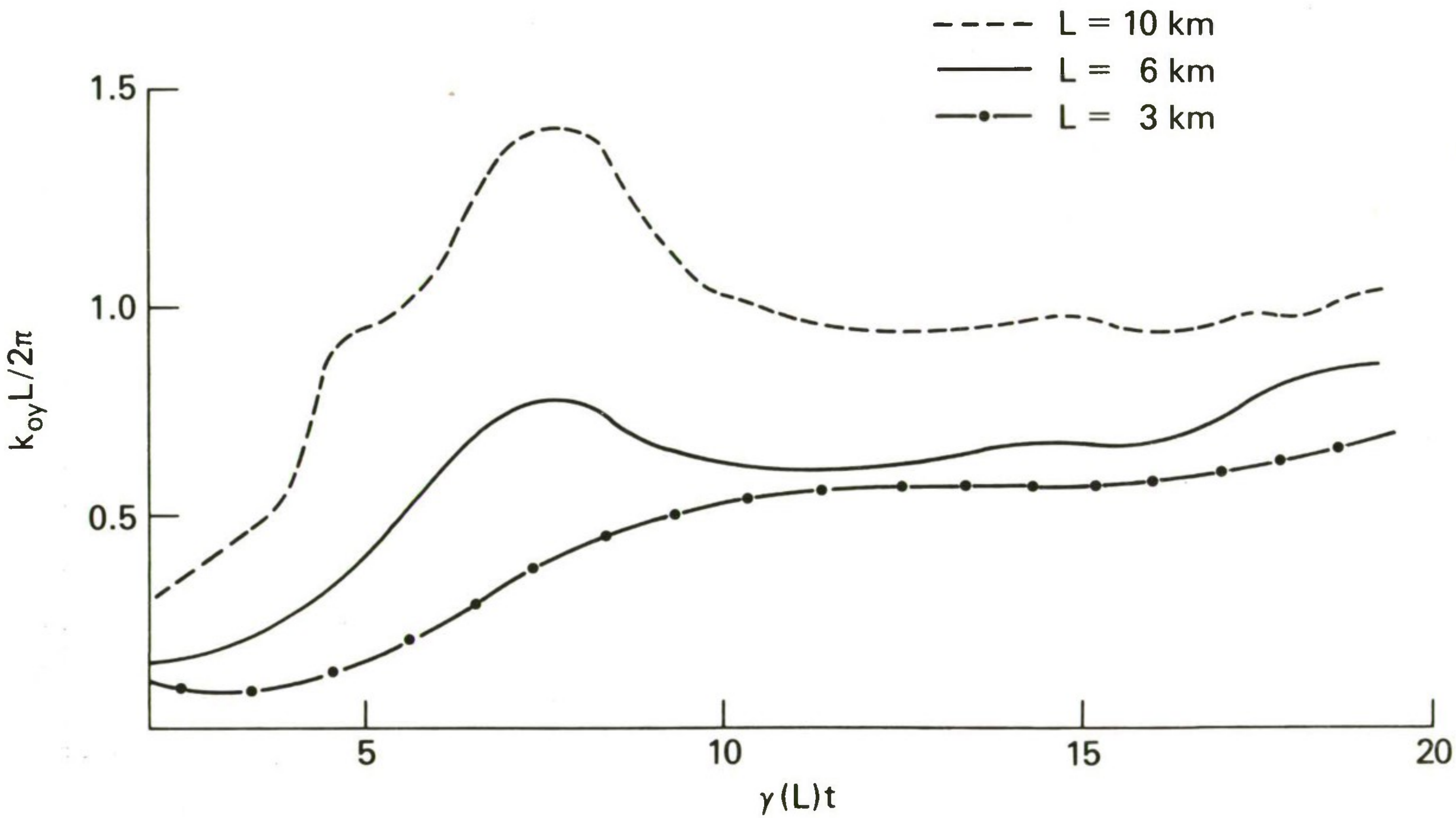

Fig. 4 - Time history of $k_{oy}L/2\pi$ for L = 3, 6, 10 km. Time t has been normalized by $\gamma^{max}(L) = cE_o/BL$.

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